A DIMENSIONAL ANALYSIS OF SUPERSATURATED TOTAL DISSOLVED GAS DISSIPATION

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ABSTRACT

Elevated levels of total dissolved gas (TDG) may occur downstream of dam discharges, leading to increased incidence of gas bubble disease in fish. Accelerating the dissipation of supersaturated TDG in the downstream river can mitigate this negative problem. However, developing effective mitigation techniques is hampered by limitations in present models of TDG dissipation processes. Furthermore, data useful for modelling the dissipation of supersaturated TDG through the free surface in natural rivers are limited. Past studies indicated that the TDG dissipation process is quantitatively different from the reaeration process, and TDG behavior is quantitatively different from dissolved oxygen. However, a correct parameterization of the TDG dissipation process is still missing.

The paper presents a novel dimensional analysis of the dissipation of supersaturated TDG. This approach can provide a relationship between the TDG dissipation coefficient and some classical fluid mechanics index-numbers. This dimensional analysis considers some key parameters for the dissipation process both water and TDG properties as well as flow characteristics, including turbulence. These parameters are water kinematic viscosity, TDG molecular diffusivity and vertical turbulent diffusivity, and channel width. The application of dimensional analysis pointed out that the TDG dissipation coefficient is a function of the Schmidt number, the aspect ratio of the channel, and the shear Reynolds number. The dimensional analysis was then verified using both field data collected in some large natural rivers and reservoirs in Sichuan and experimental data in laboratory flume at State Key Laboratory of Hydraulics and Mountain River Engineering of Sichuan University. The analysis revealed the key role of turbulence in controlling the TDG dissipation while the importance of gas/water characteristics remains still unclear and needs further investigations.

Keywords: Environmental hydraulics, supersaturated total gas dissipation, dimensional analysis.

1. INTRODUCTION

Elevated levels of total dissolved gas (TDG) may occur downstream of dam discharges, with a supersaturation level of more than 140%. The supersaturated TDG was then transported with flow to downstream rivers or reservoirs. During the process, some supersaturated TDG may dissipate and come back to the atmosphere, lowering the supersaturated level of TDG in water. According to the field observation, the dissipation process varies largely with different water bodies (Feng, et al. 2014). Due to the high pressure and weak mass transfer between air and water in deep rivers or reservoirs, the dissipation process of TDG is so slow that the supersaturation phenomenon may last for tens or hundreds of kilometers. One serious negative impact of this problem is the increased incidence of gas bubble disease in fish (Weitkamp, et al. 2008). In recent years, the TDG supersaturation problem and the consequent gas bubble decease in fish have drawn much more attention with more and more high dams being put into operation in China.

Accelerating the dissipation process, which can reduce the length of river affected by supersaturated TDG, is one of the prospective and effective mitigation measure for TDG supersaturation. However, the application of such techniques is hampered by limitations in present models of TDG dissipation processes, where the key problem is how to properly estimate the dissipation rate. Past study (Li et al, 2013) indicated that the TDG dissipation process is quantitatively different from the reaeration process, and TDG behavior is quantitatively different from dissolved oxygen. This finding demonstrated that the TDG dissipation rate cannot be proximately substitute by mass transfer rate of dissolved oxygen or other gases. However many studies about TDG supersaturation of dam discharge are mainly focusing on the generation of TDG near the dam rather than the dissipation process in the downstream rivers, and the data useful for modeling the dissipation of supersaturated TDG in natural rivers and reservoirs are limited. A more accurate and practical parameterization of the TDG dissipation process is still missing.

Under such circumstances, obtaining more experimental and field observation data and combining comprehensive scientific analysis to the limited data becomes much more critical and important for the research about the TDG mitigation techniques.

2.   STATE OF ART OF PAST STUDIES ON TDG DISSIPATION

The dissipation process of supersaturated TDG belongs to the mass transfer process which changes from supersaturation sate to equilibrium saturation state. Most of the previous studies about TDG supersaturation were focused on TDG generation process downstream of dam discharge, that is about the mass exchange from equilibrium saturation state to supersaturation sate. Roesner and Nordon (1971) first proposed a physically based model of TDG transportation in a stilling basin in which the variation of TDG level was controlled by the transfer coefficient and residence time of the bubbles in the stilling basin. An approach to predict the oxygen saturation concentration at a spillway plunge pool was later presented by Hibbs and Gulliver (1997). They used the effective saturation concentration and effective bubble depth to estimate the transfer efficiency for oxygen. The physics of bubble and free surface gas transfer were separately treated by Geldert et al. (1998), who used Azbel (1981) theory for turbulent bubble movement to develop a model for the mass transfer process across the bubble-liquid interface. Orlins and Gulliver (2000) developed a two-dimensional, laterally averaged model to predict the TDG concentration within 300 m downstream from a dam, in which both convection and turbulent diffusion through bubbles and the free surface were incorporated into the TDG mass transport. Politano et al. (1997, 2003, 2007, 2009) have simulated the TDG transport process with a two-phase flow model using a bubble density transport equation to predict the bubble size. However the mass transfer across the air-water interface was neglected. Fu et al. (2010) using an unsteady two-phase model simulated the TDG transport 3000 m downstream of Gezhouba Dam. In this model the mass transfer through the bubble-water interface and air-water surface were taken into account and the mass transfer coefficient of the air-water surface was determined by the bubble velocity and the turbulent kinetic energy, as discussed by Takemura and Yabe (1998). As the mass transfer across the bubble-water interface rather than that across the air-water surface was focused on, all these existing numerical studies about TDG generation were suitable for gas absorption process and not for desorption process. Furthermore, the TDG transfer coefficient in the models was often approximated by the reaeration coefficient of dissolved oxygen, an approach which may lead to significant misstatement (Li et al, 2013). Considering the dissipation process of supersaturated TDG in rivers downstream of stilling basins, desorption process which changes from supersaturated state to equilibrium state is dominant. A bulk dissipation coefficient that represents the overall effects of processes integrated over the river cross-section is suitable to be used. Combining field observation from the Columbia River with a first-order kinetics, the U.S. Army Corps of Engineers (USACE, 2005) proposed a predictive formula for dissipation coefficient depending from river velocity, water depth and molecular diffusion. By combining turbulent and molecular diffusion in a comprehensive coefficient in the formula proposed by USACE (2005), Feng et al (2010) proposed a modified equation for TDG dissipation coefficient according to the field data in several rivers in China. However, the comprehensive coefficient varied significantly for different rivers and reservoirs, and is difficult to specify. Finally, in agreement with more field observations and experimental data, dimensional analysis and regression were carried out by Feng et al. (2014), who proposed a formula for estimating the dissipation coefficient of supersaturated TDG in various rivers and reservoirs, involving the effects of water depth, friction velocity, hydraulic radius and Froude number. The formula was first applied in a 1-D model in predicting the supersaturated TDG along the river channel in Jinshajiang River in China. This equation still needs a broader validation.

Gualtieri et al (2002) proposed a comprehensive approach to the mass-transfer process at the air-water interface that was based on dimensional analysis. A dimensionless equation for the mass-transfer rate was developed, where the rate was a function of the Froude number, channel slope, Reynolds number, Sherwood number, Weber number, and relative roughness. The expression was then applied in reaeration study of many streams and rivers. By introducing the approach of Gualtieri et al (2002) into the TDG dissipation coefficient study, the present paper proposes an improved dimensional analysis for the TDG dissipation coefficient. This approach can provide a relationship between the TDG dissipation coefficient and some classical fluid mechanics index-numbers. This relation is then verified using a number of both field and laboratory data for the TDG dissipation coefficient.

3.   DIMENSIONAL ANALYSIS OF THE TDG DISSIPATION COEFFICIENT

The proposed approach first defines the parameters affecting the TDG dissipation process. This process should involve both fluid and TDG properties as well as characteristics of the turbulent flow in which the TDG is transported. They could be grouped as:

- fluid properties, such as the water density ρ [ML^{-3}] and the dynamic viscosity μ [$ML^{-1}T^{-1}$];
- TDG properties, such as the molecular diffusivity D_m [L^2T^{-1}];
- hydraulic and turbulence characteristic of the stream, such as the mean width W [L] and the vertical diffusivity

coefficient D_{t-z} [L²T⁻¹]. They were selected because the mean width is scaling with the exchange surface between the stream and the atmosphere and the turbulent transport of the TDG up to the surface exchange is mainly controlled by the vertical diffusivity coefficient;

Therefore, a general expression for the dissipation coefficient of supersaturated TDG K_{TDG} [T⁻¹] could be written as:

$$K_{TDG} = f_1(\rho,\, \mu,\, D_m,\, W,\, D_{t-z}) \tag{1}$$

As K_{TDG} does not contain the mass, it is more suitable to have an expression containing only kinematic parameters. So, in Eq.(1) water density and dynamic viscosity can be substituted with their ratio, i.e. the kinematic viscosity v [L²T⁻¹], to yield:

$$K_{TDG} = f_2(v,\, D_m,\, W,\, D_{t-z}) \tag{2}$$

From dimensional reasoning the vertical mixing coefficient is usually related to a turbulent length and velocity scales. They are the water depth h [L] and the shear velocity $u*$ [LT⁻¹] (Rutherford 1994, Gualtieri, 2010), that is:

$$D_{t-z} \propto h\, u* \tag{3}$$

Introducing Eq.(3) into Eq.(2), gives:

$$K_{TDG} = f_2(v,\, D_m,\, W,\, h,\, u*) \tag{4}$$

which provides the basis of the proposed dimensional analysis for K_{TDG}.

Assuming as fundamental quantities the water depth h and the molecular diffusion coefficient D_m, length and time could be obtained as:

$$[L] = [h] \tag{5a}$$

$$[T] = [h^2 D_m] \tag{5b}$$

Thus, the dissipation coefficient of supersaturated TDG K_{TDG}, and the other parameters in Eq.(1) can be defined as:

$$[K_{TDG}] = [T^{-1}] = [D_m h^{-2}] \tag{6a}$$

$$[v] = [L^2 T^{-1}] = [D_m] \tag{6b}$$

$$[u^*] = [LT^{-1}] = [D_m h^{-1}] \tag{6c}$$

$$[W] = [L] = [h] \tag{6d}$$

Finally, the dimensionless dissipation coefficient of supersaturated TDG ($K_{TDG}h/D_m$) can be expressed as:

$$\frac{K_{TDG}h}{D_m} = f_3\left(\frac{v}{D_m},\, \frac{W}{h},\, \frac{u^*h}{D_m}\right) \tag{7}$$

where the first index-number is the ratio of momentum transfer to mass transfer on molecular scale, i.e. the Schmidt number Sc and the second index-number is the aspect ratio W/h of the cross-section of the stream. The Schmidt number is a function of the fluid, the TDG as well as of the temperature. The aspect ratio can be easily measured in natural channels and it is usually even related to the strength of secondary currents. The third index-number is the product of the Schmidt number for the shear Reynolds number $Re*$, that is:

$$Re* = \frac{u^*h}{v} \tag{8}$$

On the left-hand of Eq. (7), there is the Sherwood number Sh, often used in mass-transfer theory (Incropera et al., 2006). Therefore, Eq. (7) can be finally written as:

$$\frac{K_{TDG}h}{D_m} = Sh = f_4\left(Sc,\, Re*,\, \frac{W}{h}\right) \tag{9}$$

After all, Eq. (9) demonstrates that the dimensionless dissipation coefficient of supersaturated TDG is a function of Schmidt number Sc, the aspect ratio W/h of the stream, and the shear Reynolds number of the flow $Re*$. In the next Sections, Eq. (9) will be validated using a number of field and laboratory experimental data for K_{TDG}.

4. FIELD AND LABORATORY EXPERIMENTAL DATA

The dimensional analysis above presented is to be verified using both field data collected in some large natural rivers and reservoirs in Sichuan and experimental data in laboratory flume at State Key Laboratory of Hydraulics and Mountain River Engineering of Sichuan University (SKLH) which has been studying the TDG dissipation process since 2006.

A series of field observations of supersaturated TDG dissipation were conducted during a spilling period downstream of dams on the Min River, Yangtze River, Yalong River, Jinsha River, Lancang River and Dadu River in China (Fig. 1). The TDG percent saturation levels were measured with a YSI5200 TGP/DO detector made in the USA and a PT4 TGP detector made in Canada. The accuracy of TDG measurement is about 2%. The water depth was measured combining stick ruler with hydropressure sensor with an accuracy of less than 0.1 m. The river width was measured with laser range

finder with an accuracy of less than 0.1 m. The velocity was measured using float method combined with surface velocity meter. The river slope was calculated in some cases with topographical data, whereas if topographical data were missing, the slope was estimated using Manning. The discharge rate was provided by the Hydroproject Operation Department and verified with Manning equation. The data indicate that the supersaturated TDG dissipated slowly in some large rivers such that its influence was observed for tens to hundreds of kilometers downstream of the spillway. Along more than 600 kilometers downstream of the Three Gorges Dam, the TDG saturation was observed to be over 100% .

If we assume that the cross-section TDG saturation is relatively uniform and provides a reasonable basis for modeling longitudinal dynamics, a 1-D model for the supersaturated TDG dissipation process following first-order kinetics theory is

$$\frac{d(G - G_{eq})}{dt} = -K_{TDG}(G - G_{eq}) \tag{10}$$

where G denotes the percent saturation of TDG at time t, G_{eq} represents the equilibrium percent saturation of TDG and is assumed to be 100% .

Feng et al. (2010) analyzed the TDG field data applying the curve-fitting method with the longitudinal dissipation model. The dissipation coefficients were computed for different rivers, denoted as cases from F1 to F11, listed in Table 1. The same method was used on an additional data set to estimate K_{TDG} in Dachaoshan Reservoir, Dadu River and Tongjiezi Reservoir, which are also listed in Table 1.
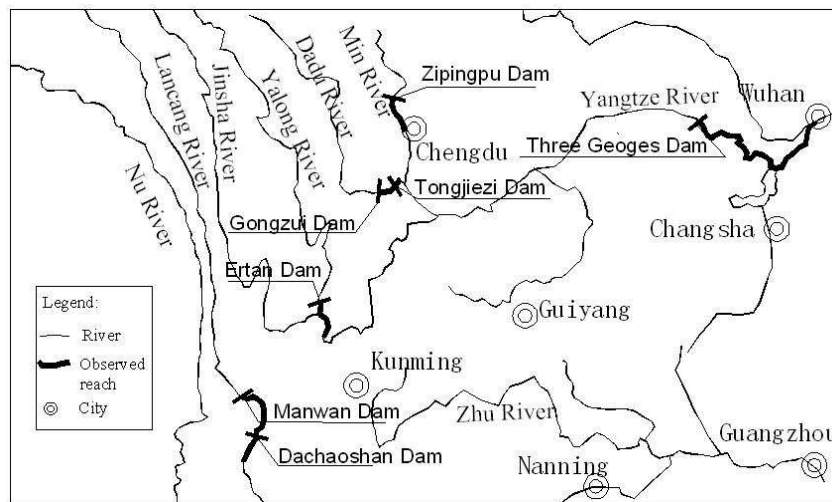

Figure 1. Locations of the field study

A number of dissipation experiments on supersaturated TDG in open channel flow were conducted at SKLH (Fig.2). The open channel was made of glass, with a length of 18 m, a width of 0.15 m and a height of 1 m. The channel slope was 0.04% . A flow of water with supersaturated TDG was generated using an autoclave. Air and water were pumped into the autoclave through different inlets and mixed under high pressure so that supersaturated conditions were obtained. The flow was directed into the channel through an outlet pipe on the autoclave. The flow rate was controlled by a valve on the autoclave, and the TDG concentration was controlled by both the pressure valve and the flow rate. Two observation sections were located upstream and downstream of the channel with a distance of 17 m. The percent saturation of TDG was measured with PT4 TGP detectors made in Canada. The water depth was measured with a steel ruler with an accuracy of about 1 mm. K_{TDG} values were calculated using Eq. (10). The experimental data are listed in Table 2 as cases from L1 to L10.
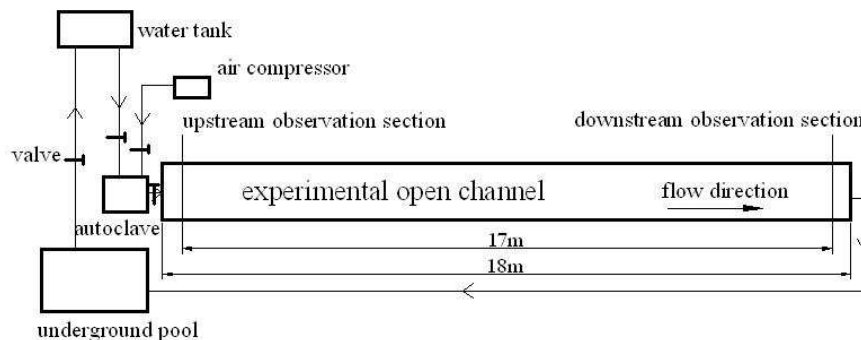

Figure 2. Sketch of the experimental facility for supersaturated TDG dissipation at the SKLH

Table 1. Experimental field data

Case No.	Experimental Location	Slope	W - m	h - m	W/h	R_h - m	u – m/s	u^* - m/s	Sc	Re*	K_{TDG} - 1/s
F1	Yalong River	0.00226	480	10.0	48	9.60	3.332	0.471	543.98	4.6E+06	2.75E-05
F2	Yalong River	0.00226	259	7.4	35	7.00	2.785	0.405	585.42	2.8E+06	2.68E-05
F3	Jinsha River	0.00093	530	10.5	51	10.10	3.389	0.310	664.28	2.9E+06	1.72E-05
F4	Jinsha River	0.00093	714	10.5	68	10.20	3.396	0.310	664.28	2.9E+06	1.67E-05
F5	Yangtze River	0.00060	2600	19.9	131	19.60	2.660	0.342	440.66	7.5E+06	3.89E-06
F6	Yangtze River	0.00060	1069	16.6	64	16.10	2.910	0.313	440.66	5.6E+06	5.56E-06
F7	Baitiao River	0.00413	198	3.2	62	3.10	2.920	0.360	919.28	8.7E+05	1.56E-04
F8	Zouma River	0.00413	174	3.0	58	2.90	2.920	0.349	919.28	7.9E+05	1.81E-04
F9	Lancang River	0.00212	286	6.7	43	6.40	2.294	0.373	557.36	2.4E+06	2.94E-05
F10	Lancang River	0.00212	336	8.4	40	8.00	2.776	0.418	543.98	3.4E+06	2.65E-05
F11	Lancang River	0.00212	360	7.5	48	7.20	2.550	0.395	531.03	2.9E+06	2.81E-05
F12	Dadu River down. Tongjiezi Reser.	0.00172	168	4.2	40	4.00	2.240	0.266	647.44	9.9E+05	5.59E-05
F13	Lower Reach of Dadu River	0.00172	852	6.9	123	6.79	2.020	0.341	664.28	2.1E+06	2.61E-05
F14	Dachaoshan Reser. on Lancang River	0.00212	598	25.2	24	23.24	0.821	0.724	543.98	1.7E+07	8.33E-07

Legend: W=width; h=flow depth; R_h=hydraulic radius; Sc=Schmidt number; Re*=shear Reynolds number; K_{TDG}= dissipation coefficient of TDG.

Table 2. Experimental laboratory data

Case No.	Experimental Location	Slope	W - m	h - m	W/h	R_h - m	u – m/s	u^* - m/s	Sc	Re*	K_{TDG} - 1/s
L1	Laboratory Flume	0.00041	0.15	0.040	3.75	0.026	0.056	0.010	421.30	3.1E+02	3.83E-04
L2	Laboratory Flume	0.00041	0.15	0.040	3.75	0.026	0.063	0.010	377.53	3.2E+02	4.00E-04
L3	Laboratory Flume	0.00041	0.15	0.045	3.33	0.028	0.075	0.011	394.28	3.6E+02	4.36E-04
L4	Laboratory Flume	0.00041	0.15	0.045	3.33	0.028	0.076	0.011	377.53	3.6E+02	4.36E-04
L5	Laboratory Flume	0.00041	0.15	0.050	3.00	0.030	0.075	0.011	421.30	3.8E+02	5.67E-04
L6	Laboratory Flume	0.00041	0.15	0.050	3.00	0.030	0.076	0.011	394.28	3.9E+02	5.89E-04
L7	Laboratory Flume	0.00041	0.15	0.055	2.73	0.032	0.078	0.011	403.02	4.2E+02	4.58E-04
L8	Laboratory Flume	0.00041	0.15	0.055	2.73	0.032	0.078	0.011	385.79	4.3E+02	6.28E-04
L9	Laboratory Flume	0.00041	0.15	0.060	2.50	0.033	0.078	0.012	412.03	4.5E+02	7.69E-04
L10	Laboratory Flume	0.00041	0.15	0.060	2.50	0.033	0.076	0.012	385.79	4.6E+02	4.94E-04

Legend: W=width; h=flow depth; R_h=hydraulic radius; Sc=Schmidt number; Re*=shear Reynolds number; K_{TDG}= dissipation coefficient of TDG.

5. APPLICATION OF THE DIMENSIONAL ANALYSIS TO THE EXPERIMENTAL DATA.

Eq. (9) suggested that the dimensionless dissipation coefficient of supersaturated TDG is a function of Schmidt number *Sc*, the aspect ratio *W/h* of the stream, and the shear Reynolds number of the flow *Re**. First, field and laboratory experimental data were separately plotted against the above three index-numbers derived from the dimensional analysis.
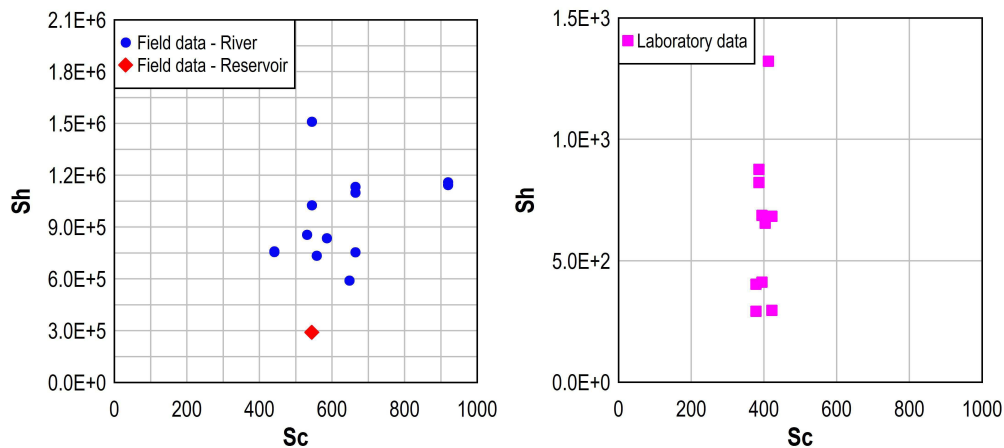

Figure 3. Dimensionless dissipation coefficient of supersaturated TDG *Sh* vs *Sc* for (left) field and (right) laboratory data

Fig.3 shows the dimensionless dissipation coefficient of supersaturated TDG against the Schmidt number *Sc* for the field data (left) and the laboratory data (right), respectively. Field data were collected in a range of *Sc* from 440 to 919, while the laboratory data belonged to a narrow range of values, i.e. from 385 to 421. It could be noted that both for field and laboratory data, the effect of *Sc* of dissipation remains unclear. This is probably due to the large uncertainties related to the estimation of molecular diffusivity for the TDG. In fact, for the plots in Fig.3, as a first approximation the molecular diffusivity of dissolved oxygen was used as a proxy of TDG molecular diffusivity.

Fig.4 shows the dimensionless dissipation coefficient of supersaturated TDG against the aspect ratio *W/h* of the stream for (left) the field data and (right) the laboratory data, respectively. The field data were collected in cross-sections with an aspect ratio in the range from 24 to 123, which is typical of natural channels. The experiments carried out in at SKLH were characterized a *W/h* in the range from 2.50 to 3.75, that is the case of *narrow* channels (*W/h*<5). A different trend was observed. In the field data, dissipation of the supersaturated TDG increased with the aspect ratio. The value collected in the Dachaoshan Reservoir corresponding to *W/h*=24, was quite aligned with the data collected in rivers. On the opposite, for the laboratory data, the largest values of the Sherwood number were observed for the smallest *W/h* and the dissipation rate decreased with the increasing aspect ratio. Since more than one century it was reported that in both open channels and rivers for an aspect ratio *W/h*<5 the location of the maximum velocity is below the free surface (*z/h*≈0.6–0.7) producing the dip-phenomenon with a three-dimensional flow (Francis 1878; Nezu and Nagakawa 1993; Graf and Altinakar 1998). This phenomenon is due to the influence of sidewalls on the centerline velocity distribution and, in particular, to a strong vortex occurring near the free surface which transfers momentum and energy from the side wall toward the channel center and, consequently, towards the channel mid-depth and bed (Nezu and Nagakawa 1993, p.102). Hence, the occurrence of the dip-phenomenon is related to the presence of strong secondary currents. They are also called *turbulence-driven secondary currents* because are formed as a result of turbulence heterogeneity and anisotropy (Nezu and Nakagawa 1993). Fig.4, right, highlighted the role of secondary currents in increasing the dissipation of the supersaturated TDG. Notably, a similar trend with *W/h* was observed for the values of the turbulent transverse mixing coefficient collected in straight laboratory channel for *W/h*<10 (Gualtieri and Mucherino 2007, Fig.6; Gualtieri 2011, Fig.1).
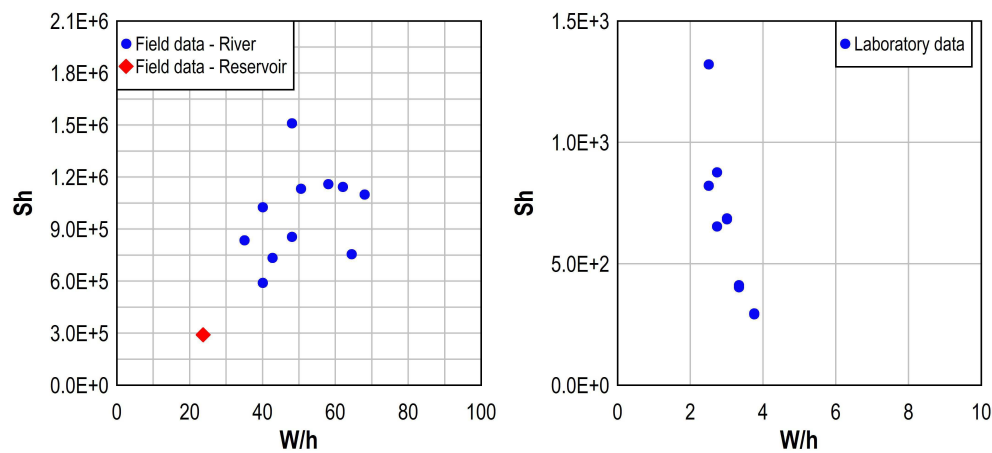

Figure 4. Dimensionless dissipation coefficient of supersaturated TDG *Sh* vs *W/h* for (left) field and (right) laboratory data

Finally, Fig.5 shows the dimensionless dissipation coefficient of supersaturated TDG against the shear Reynolds number *Re** for (left) the field data and (right) the laboratory data, respectively. The field data were collected in cross-sections with a *Re** in the range from 7.9E+05 to 1.7E+07, while the laboratory data belonged to the range from 310 to 460.

For the experimental rivers data, the dissipation rate generally increased with the increasing *Re**. The value from Dachaoshan Reservoir presented a lower dissipation rate despite its larger *Re**. This is probably related to the different mechanism which responsible for turbulence production in a river (*bottom-shear generated turbulence)* and in a reservoir *(wind-shear generated turbulence)*. This difference is believed to largely affect interfacial exchange across the air-water interface (Gualtieri and Pulci Doria 2012).

For the laboratory data, the dimensionless dissipation coefficient of supersaturated TDG largely increased with the increasing *Re**.

After all, the analysis of the experimental data demonstrated the key role of turbulence on the process of dissipation of supersaturated TDG. In fact turbulence is affecting the intensity of the dissipation of supersaturated TDG both directly by mean of the shear Reynolds number *Re** (Fig.5) and through the action of the secondary currents in the narrow channels (Fig.4, right). On the other hand, the effect of the characteristics of TDG at the molecular scale, i.e. molecular diffusivity and Schmidt number, needs further investigations.
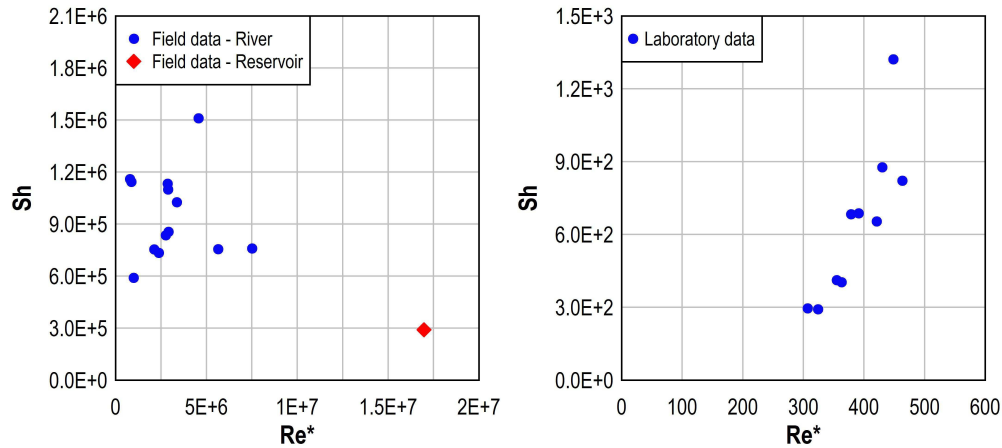
Figure 5. Dimensionless dissipation coefficient of supersaturated TDG *Sh* vs *Re** for (left) field and (right) laboratory data

6. CONCLUSION

Elevated levels of total dissolved gas (TDG) may occur downstream of dam discharges, leading to increased incidence of gas bubble disease in fish. Hence, it is very important to gain a better knowledge on the physical mechanisms controlling the dissipation of the TDG across the air-water interface.

The paper presented a novel dimensional analysis of the TDG dissipation process which considers as key parameters both water and TDG properties as well as flow characteristics, including turbulence. First, the dimensional analysis gained a relation in which the dimensionless dissipation rate is a function of the Schmidt number *Sc*, the aspect ratio of the channel *W/h*, and the shear Reynolds number *Re**. Second, a comparison with both field and laboratory experimental data highlighted that the turbulence is a key parameter of the dissipation process whose rate increased with the increasing *Re**. Furthermore, turbulence affected the process as it increased the strength of secondary currents in laboratory channels with a low aspect ratio, which, in turn, enhanced the dissipation rate. Third, the role of the gas/water characteristics, i.e. of the Schmidt number, remained still unclear probably due to the large uncertainties related to the estimation of molecular diffusivity for the TDG. Future investigations should be addressed to clarify this role as well as to extend the present findings to the intermediate range of shear Reynolds number.

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